Parallel Session 3: Lunar Geophysics & Magnetics Overview Talk

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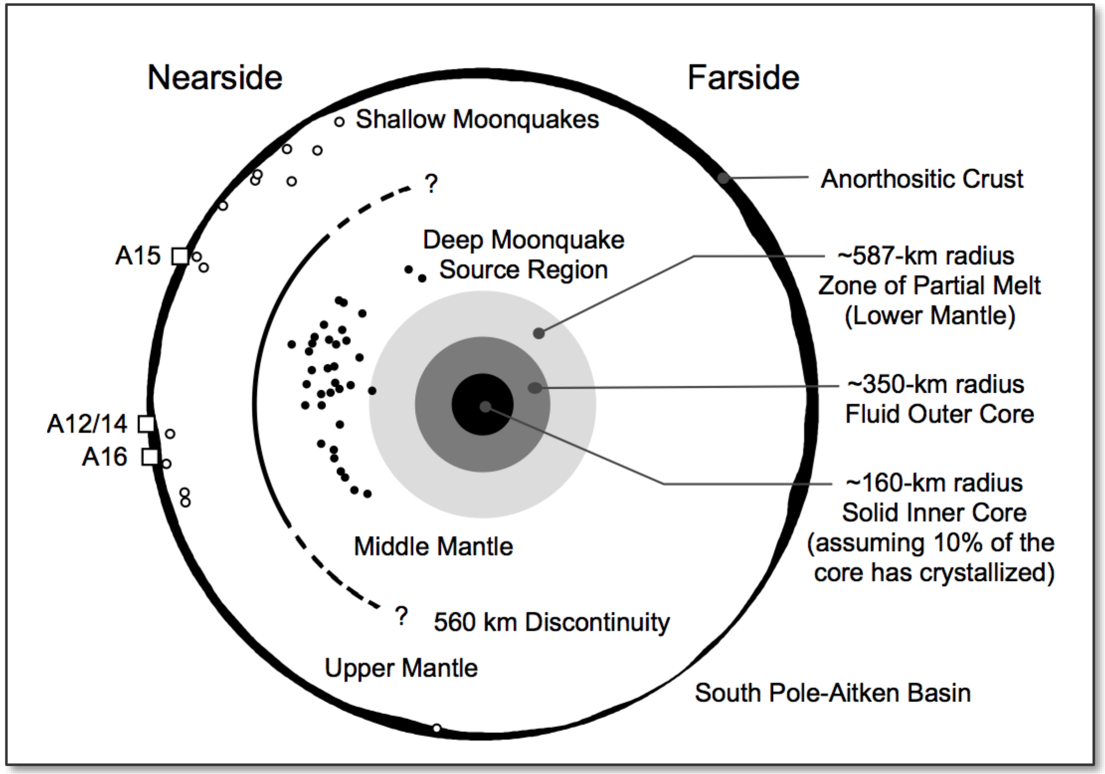
Geophysics: elucidating the lunar interior

- Interior properties (layering, composition, seismic velocity and density, presence of partial melt, core state: liquid vs. molten) provide important constraints on lunar formation and evolution models, as well as possible indicators of an early dynamo for magnetic field generation.

- Constraints on these properties arise from geophysical observations:
  - ➢ Seismology
  - ➢ Heat flow
  - ➢ Geodetic parameters and lunar laser ranging
  - ➢ Magnetic induction studies
  - ➢ Gravity field

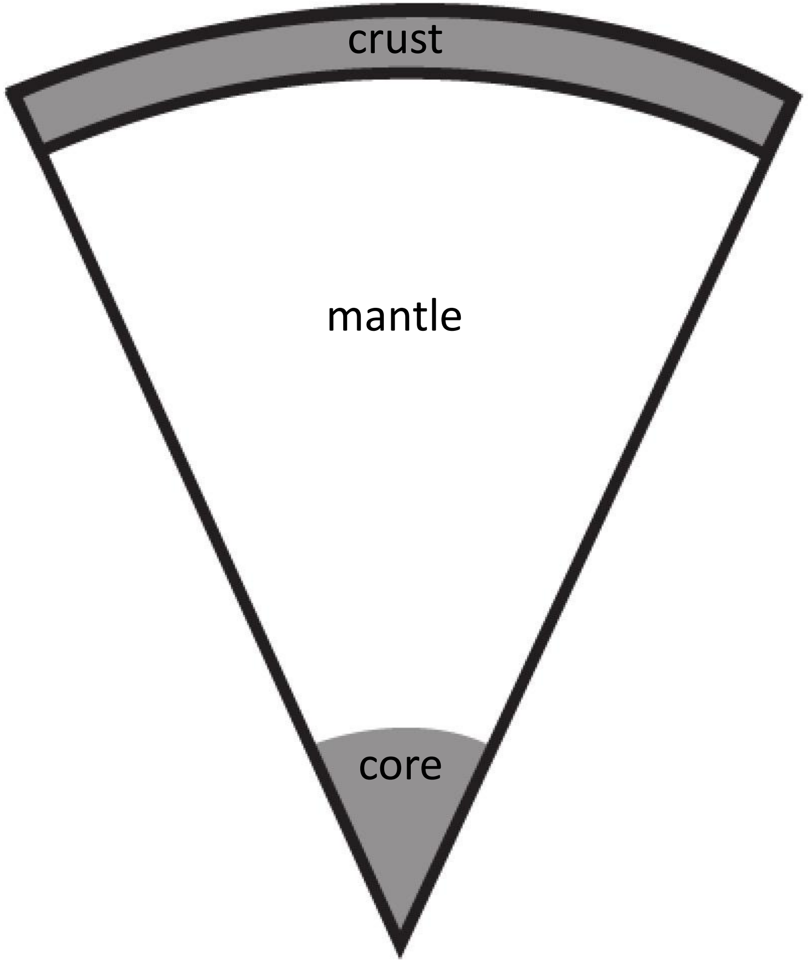


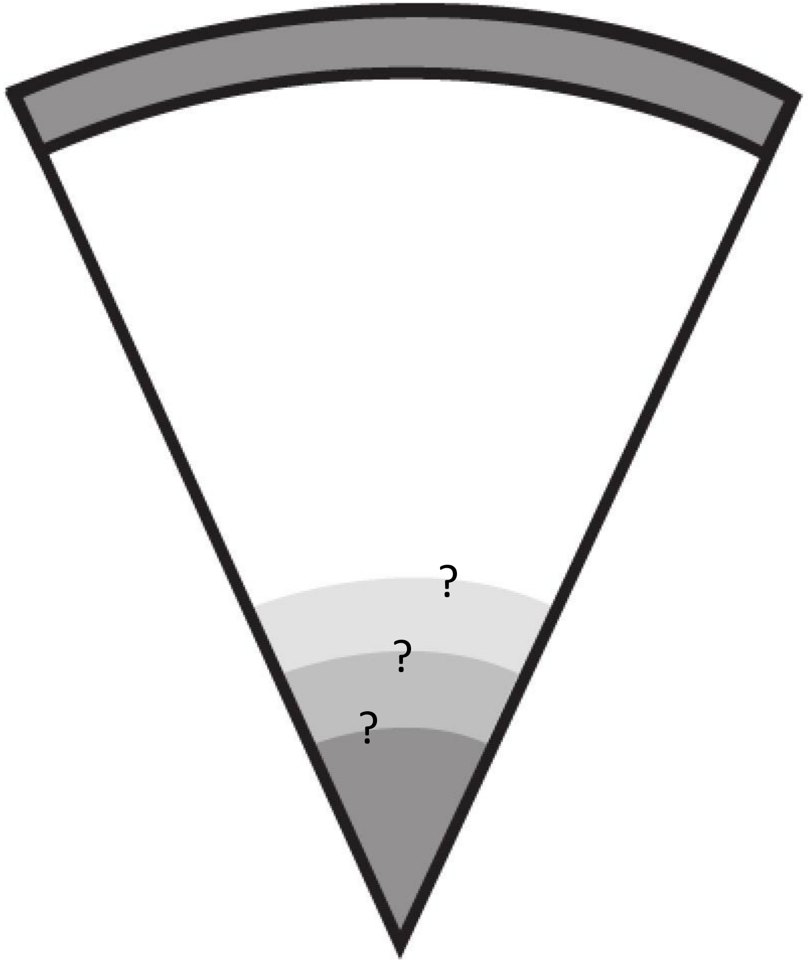
Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.

Understanding prior to re-analysis of Apollo data and the GRAIL lunar gravity mission

Moon's moment of inertia roughly approximated by homogeneous sphere ($I_{solid}/MR^2 = 0.3930 \pm 0.0003$)

If a core is present, it must be small.



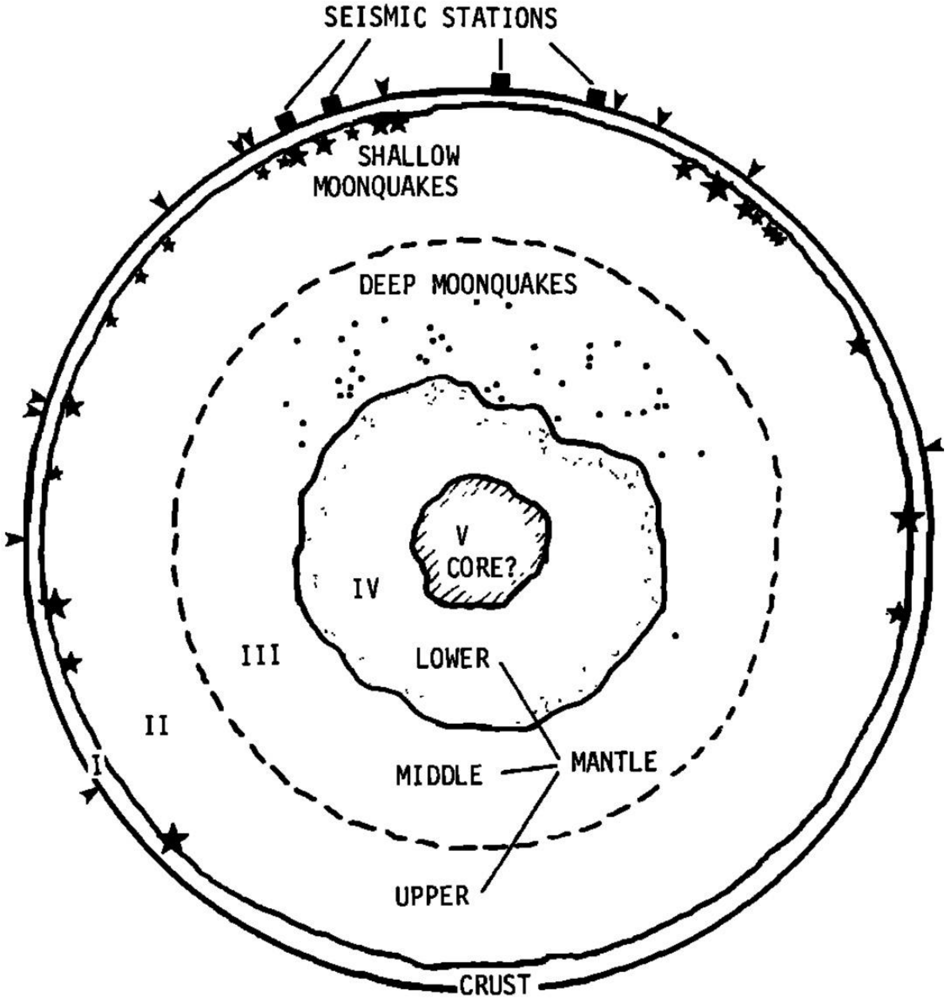


Seismic measurements found…

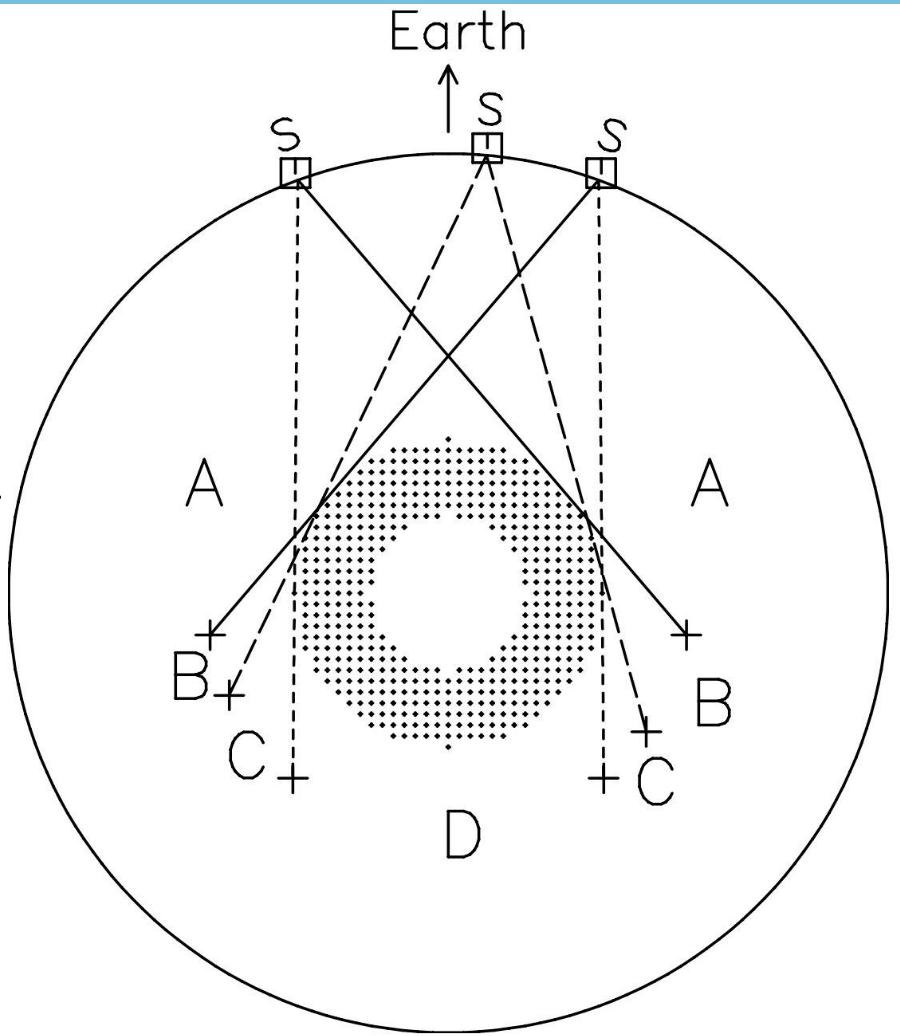
No seismic energy originating from far side penetrated the core, so it is likely attenuating

Deepest moonquake source regions ~1200-1400km depth; so core likely 300-500km radius

Wieczorek et al. (2013) *Science* **339**, 671-675



Nakamura (1983) *GRL* **88**, 677-686



Nakamura (2005) *JGR* **110**

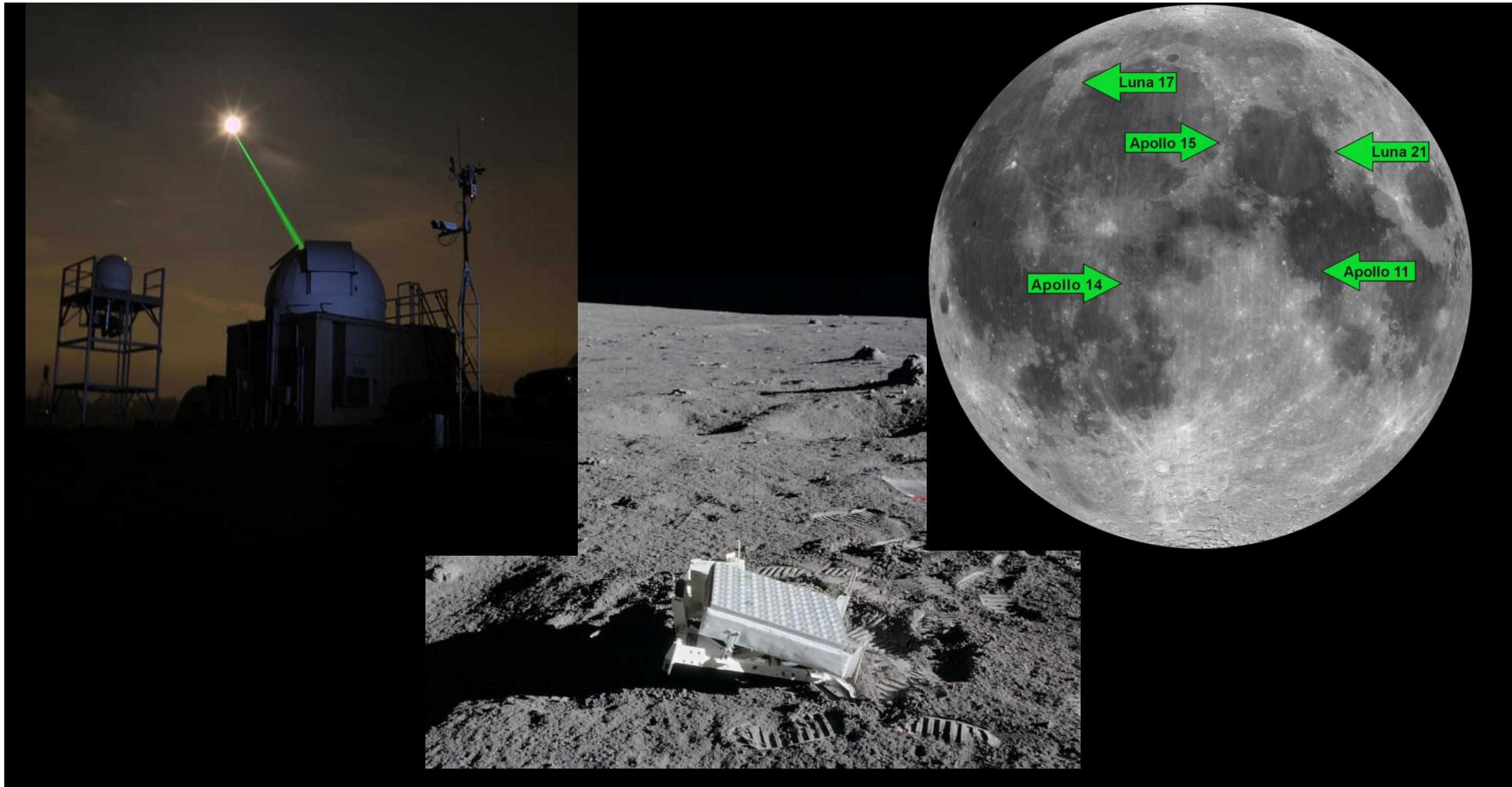
Indirect measurements found…

Lunar Laser Ranging (LLR):

LLR began precise monitoring of the Moon’s geodetic parameters in 1969

Dissipation provided the first LLR evidence for a fluid core

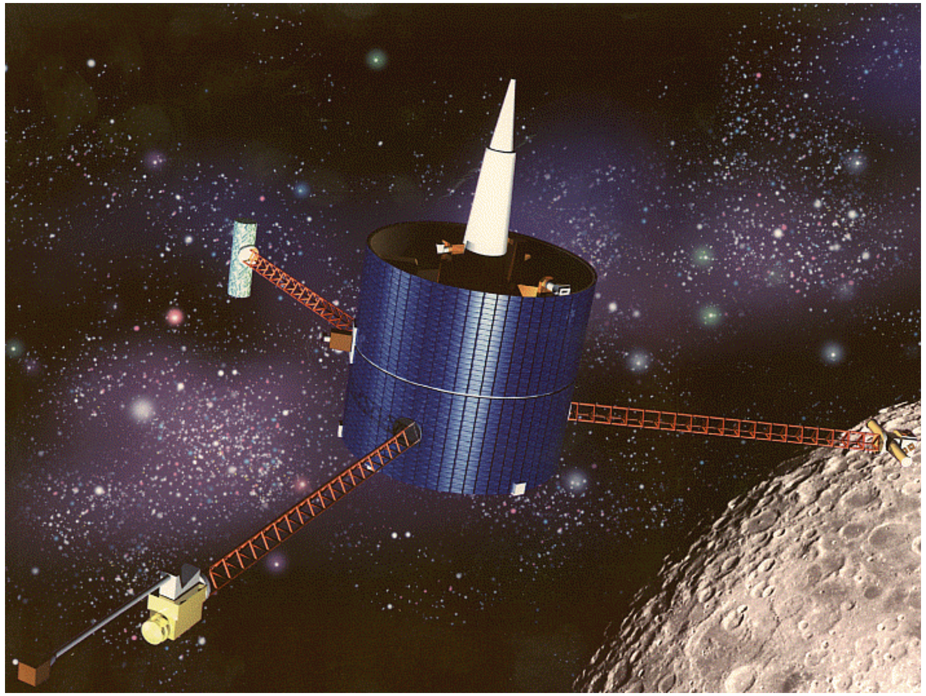
fluid core radius = 352km if iron, or 374km for a Fe-FeS eutectic composition

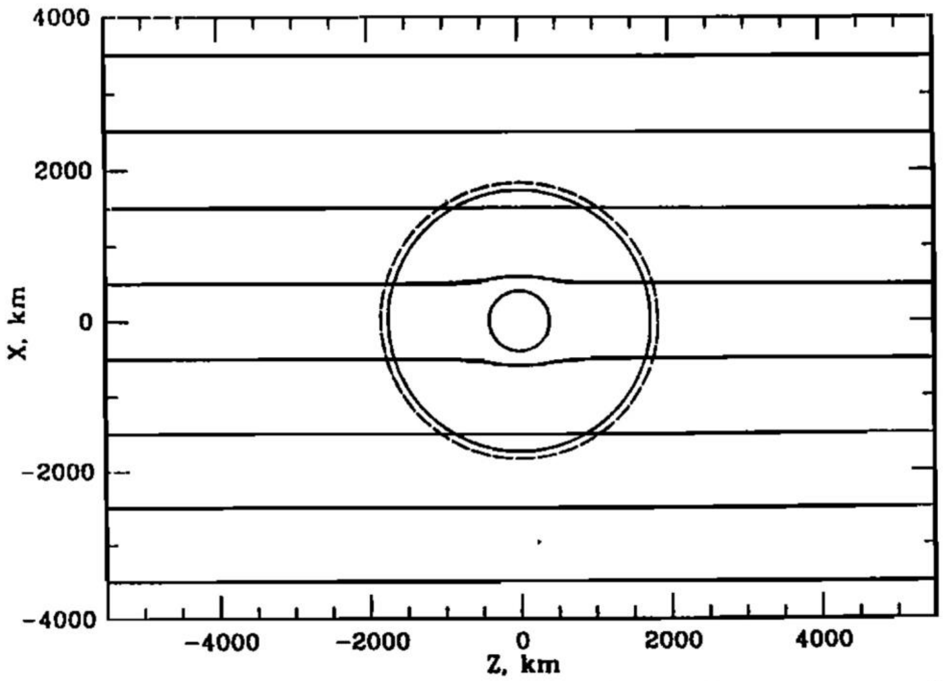


Indirect measurements found…

Magnetic Induction

- In April of 1998, the Lunar Prospector orbit plane was nearly parallel to the Sun-Moon line, optimally oriented for using the magnetometer to detect an induced moment in the Earth's geomagnetic tail
- Assuming that the induced field is caused entirely by electrical currents near the surface of a highly electrically conducting metallic core, the preferred core radius = 340+90 km.
- For an iron-rich composition such a core would represent 1 to 3% of the lunar mass



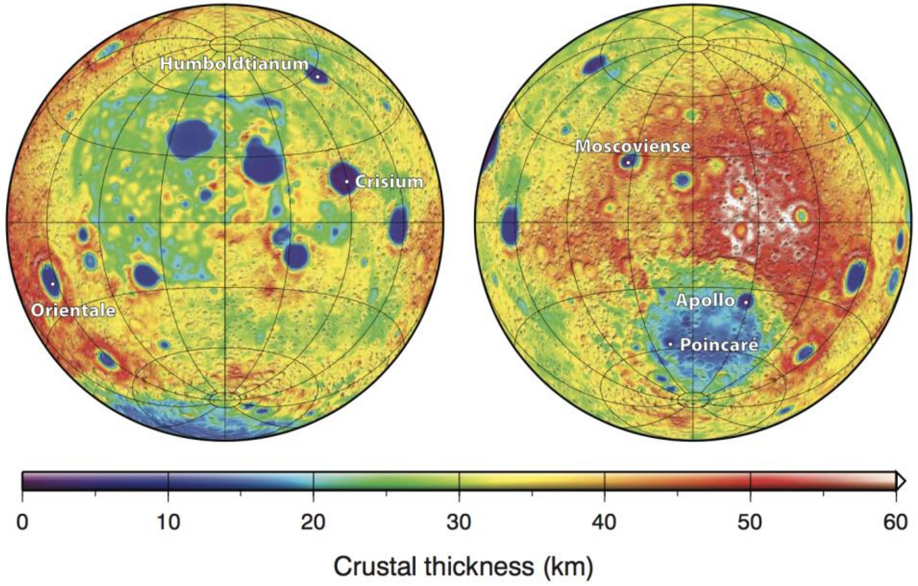


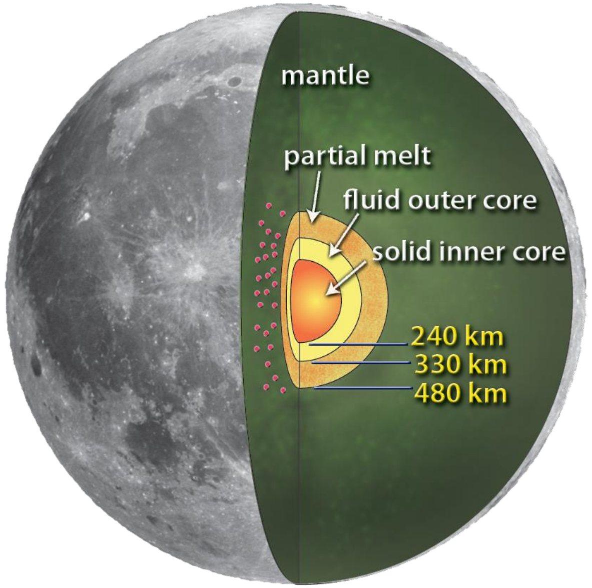
Hood et al. (1999) *GRL* **26**, 2327-2330

Recent advances in lunar geophysics

- GRAIL lunar gravity mission mapped the Moon's gravity field in extreme detail
  - Shallow (crustal) structure tightly constrained, but still tied to (uncertain) ground-truth seismic estimates from the Apollo landing sites
- Re-analyses of Apollo seismic data found evidence for core reflections, including the presence of a partial melt layer above the liquid outer core
  - Differing perspectives on whether a partial melt layer is required to satisfy available constraints (gravity, seismic, geodetic constraints, EM sounding data, phase-equilibrium models, dissipation)

Wieczorek et al. (2013) *Science* **339**, 671-675

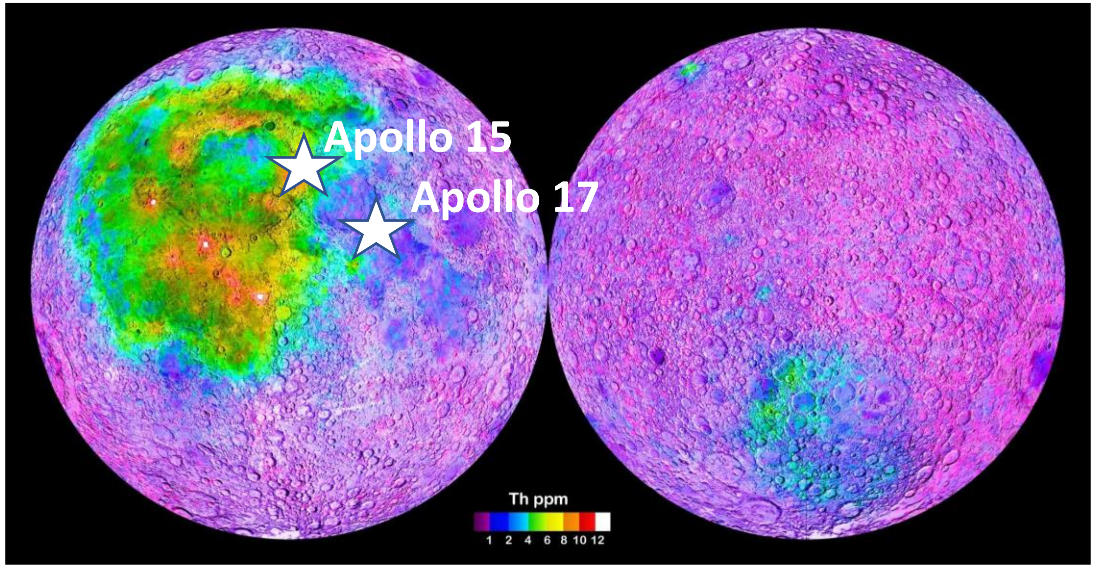


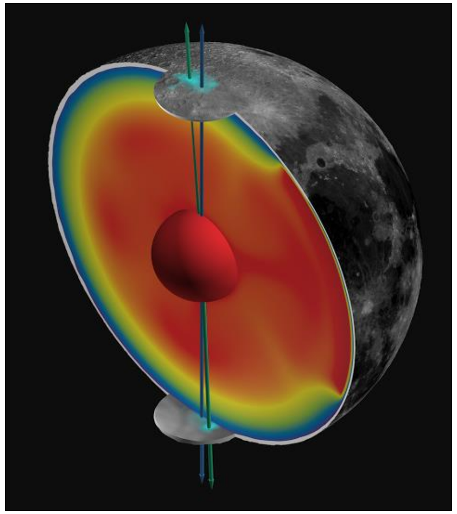


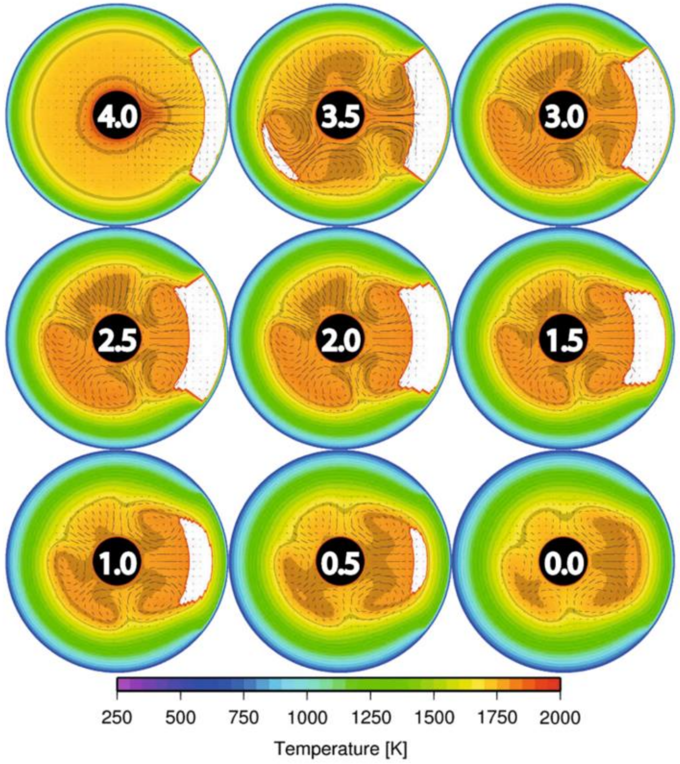
Weber et al. (2011) *Science* **331**, 309-312

Synergy with geothermal measurements

- Geothermal measurements track heat production and interior temperature distribution.
- The Apollo Heat Flow Experiments were both within areas dominated by Thorium-rich crust. How the PKT came to exist depends on internal structure.
- Determining the structure of the lunar core and deep interior is critical for understanding the Moon's formation. Geophysical data reveal the evolution of the lunar dynamo, by which the Moon may have generated and maintained its own magnetic field. They also provide context for thermal emission and volcanism studies.





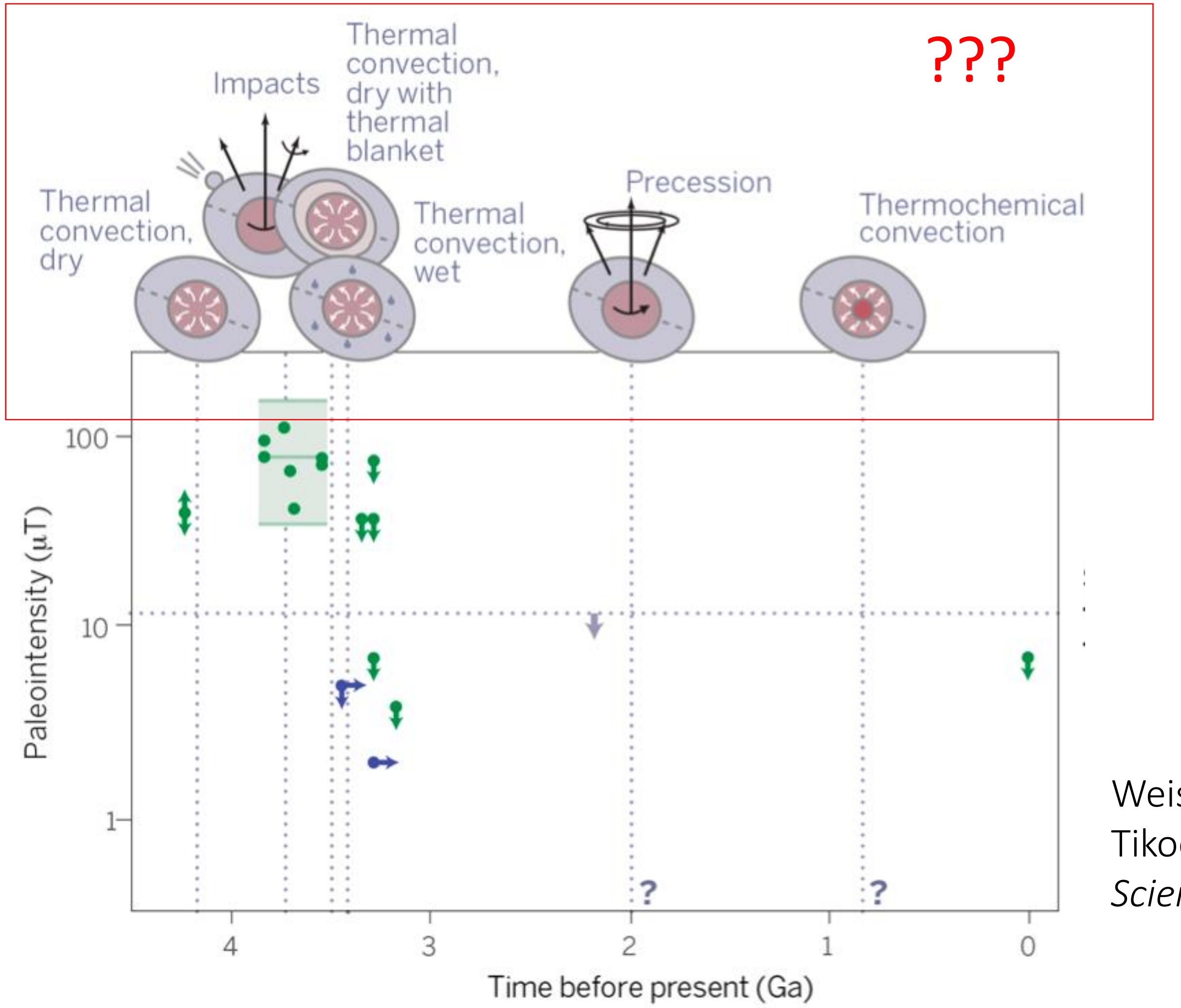


Laneuville et al. (2014) *EPSL* **401**, 251-260.

Both deep structure and magnetism have bearing on the lunar dynamo

- Magnetism is ubiquitous in the solar system.
- We don't know the nature of the extinct lunar dynamo - surprising it even existed on such a small body.
- Still no published numerical models of dynamo generation.
- Implications for lunar thermal history, core state

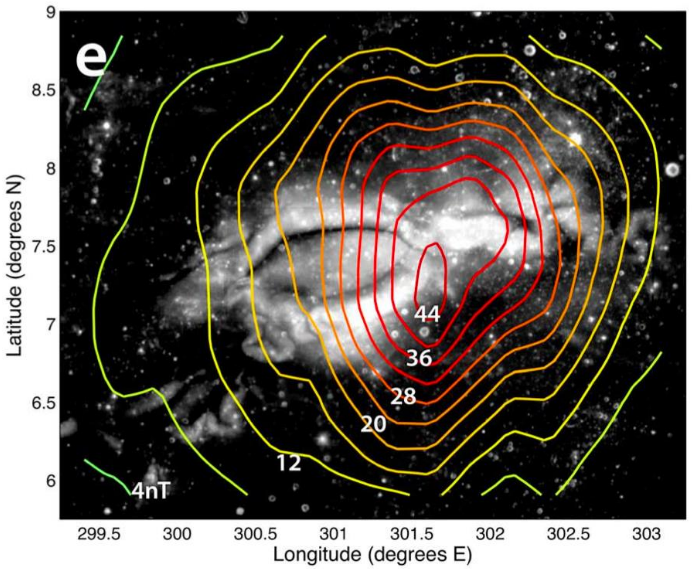
Oldest paleomagnetic measurement: 4.25 Ga (Garrick-Bethell et al. 2017. *JGR* **122**)



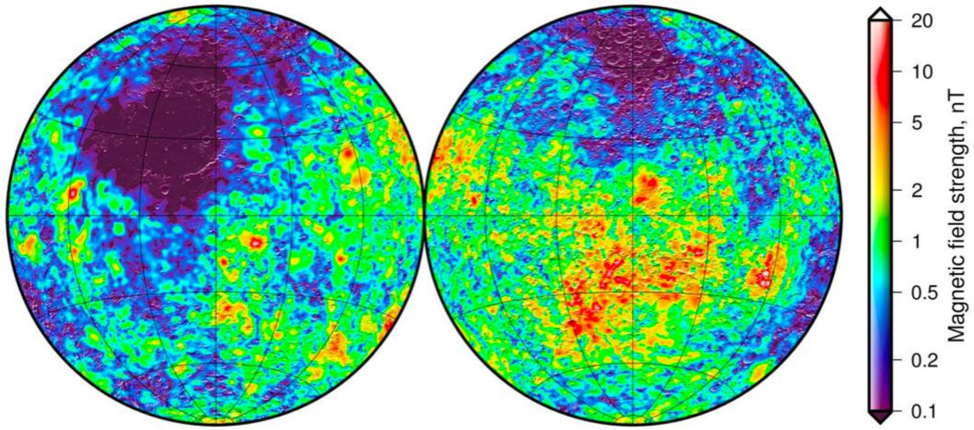
Weiss & Tikoo (2014) *Science* **346**.

Lunar dynamo & crustal magnetism

- Constrain dynamo history with paleomagnetism
- Constrain via crustal magnetism studies
    - We don’t know the exact geologic origin of *a single one of the Moon’s magnetic anomalies* (!)
        - Compare with our ignorance of seafloor anomaly origins on Earth in the 1940s



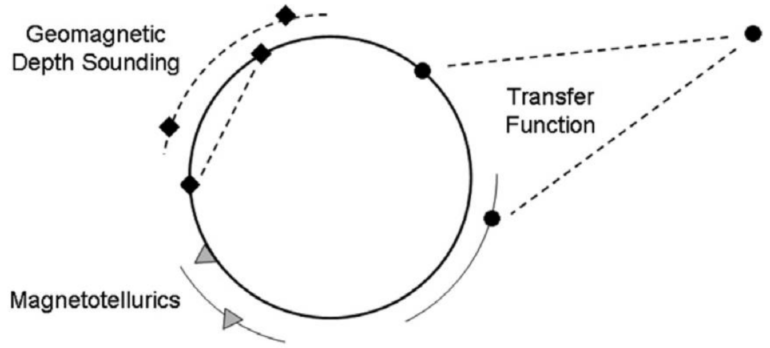
Local crustal magnetism – Hemingway & Garrick-Bethell (2012) *JGR* **110**

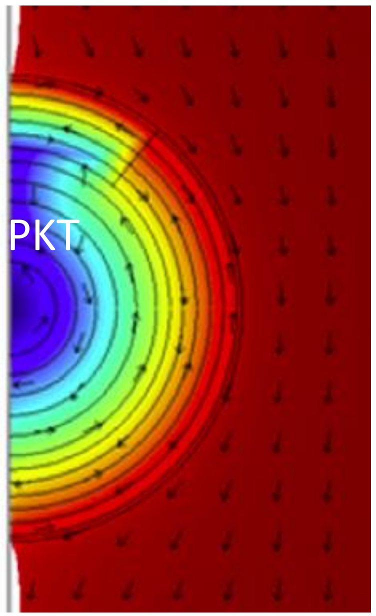


Global-scale crustal magnetism – Wieczorek et al. (2017) *NVOTM2* #6036

Global-scale magnetic induction

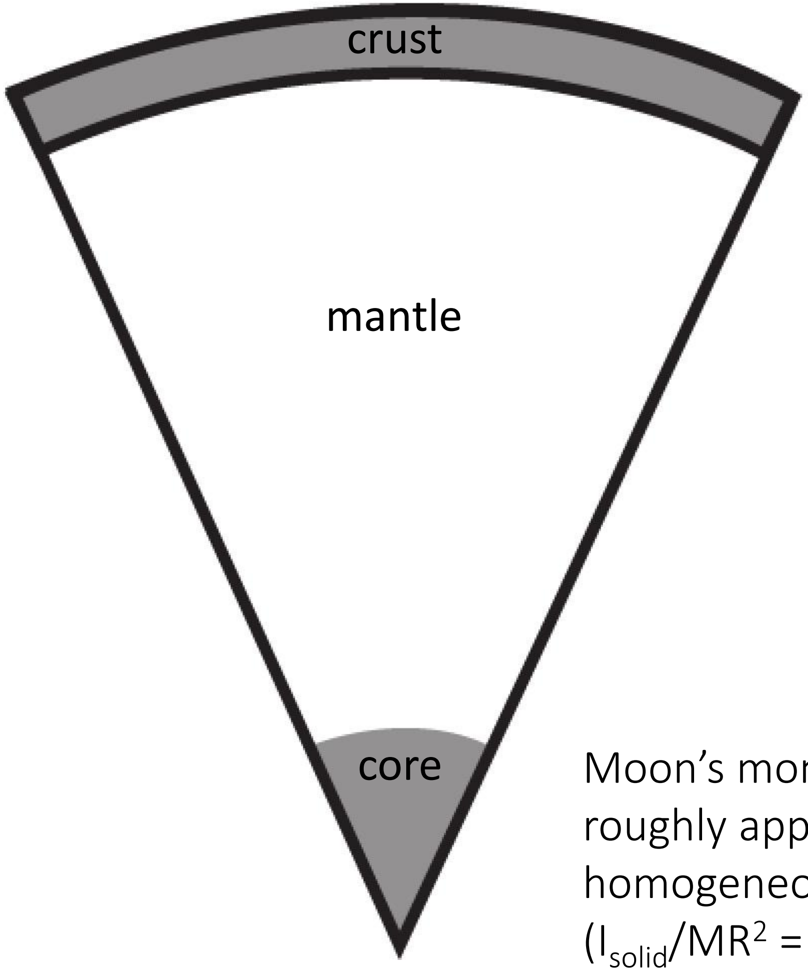
- Mantle temperatures at global scale could be measured with a pair of orbiting magnetometers
  - Demonstrated at single points at the Apollo stations.

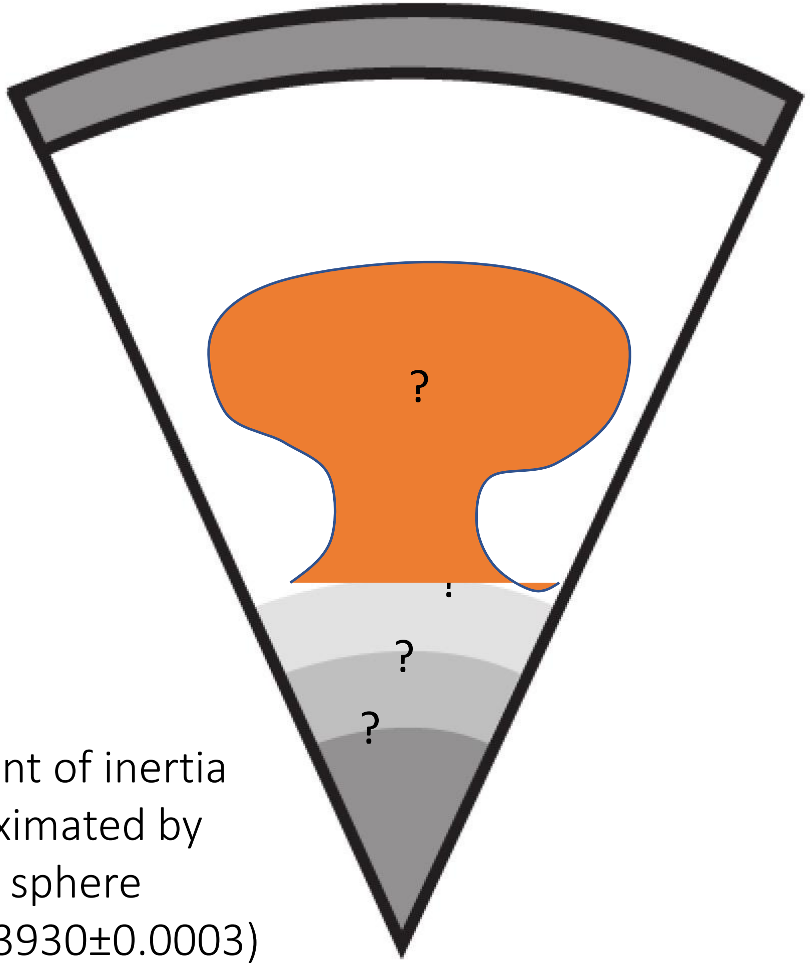




Simulated electric field due to background magnetic field oscillations, highlighting a warm conductive region at the PKT.
(Grimm & Delory 2012), *Adv. Space Res.* **50**

How to develop an internal structure model consistent with all observations?





Moon’s moment of inertia roughly approximated by homogeneous sphere ($I_{solid}/MR^2 = 0.3930 \pm 0.0003$)

The Lunar Geophysical Network – What is it?

JPL LUNETTE mission concept

- A network of geophysical "nodes" (at least 4) operating continuously for an extended period of time – at least 2 (ILN), 4 (LUNETTE), or 10 (LGN) years
- Science objectives for each node:

Seismometer	Heat flow probe	Retroreflector	Magnetometer
• Understand the current seismic state and determine the detailed internal structure of the Moon	• Measure the heat flow to characterize the temperature structure of the lunar interior	• Increase ability to determine deep lunar structure and conduct tests of gravitational physics by installing next-generation laser ranging capability	• Use electromagnetic sounding to measure the electrical conductivity structure of the lunar interior